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A SIMULATION FRAMEWORK FOR FRESHWATER EUTROPHICATION MANAGEMENT

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ABSTRACT

Anthropogenic pollution and natural decay processes of organic material provide changes of water quality within rivers and lakes. These processes influence the functioning of freshwater ecosystems and result in restricted water uses. A sustainable management of freshwater ecosystems can be achieved by using simulation models combined with optimisation procedures. For this reason a simulation framework (CEUS) was developed for a river lake-system including phosphorus remobilisation from sediment. CEUS was carried out within the MATLAB development environment. For parameter optimization CEUS was combined with the software tool ISSOP. The simulation framework was applied to the Lower Havel River basin. For water quality management two decision control strategies are discussed.

Index Terms **–** Modelling, simulation, optimisation, eutrophication, water quality management

1. INTRODUCTION

The functioning of freshwater ecosystems and various water uses are affected by natural and man induced pollution processes. While natural pollution is mostly small the nutrient input due to land erosion and intensive anthropogenic activities in a river basin force the eutrophication processes which is characterised by an increase of dissolved nutrients in water bodies, mainly phosphorus, carbon and nitrogen, by excessive growth of green plants, and by restricted water uses due to anoxic water conditions as well as by odour problems.

Eutrophication processes of freshwater ecosystems are supported by intensive man-made activities in river basins due to industry and agriculture as well as by domestic water uses. Therefore, pollution will be more indicated by eutrophication effects but less by actual changes of nutrient and suspended matter concentrations. On the other hand, sediments have been accumulated nutrients over several decades [2]. In the case of oxic water conditions they are stored within the sediment. Changing the water quality status from oxic to anoxic conditions due to high level dissolved oxygen demand by bacteria the sediments act as internal nutrient sources [1].

To evaluate the algal dynamics due to nutrient influences of a lowland river-lake system the simulation framework CEUS (**C**ottbus **EU**trophication **S**imulator) was worked out within the MATLAB development environment. The combination of CEUS with the software tool ISSOP, which was originally developed for manufacturing, organisational and logistic processes [5], allows optimal parameter estimations [7]. The modelling and simulation framework was applied to the catchment area of the lowland rivers Havel and Spree close to the Berlin/Potsdam region.

In this paper, simulation results are presented for important water quality indicators as phytoplankton (algal) biomass, phosphate phosphorus, ammonia nitrogen and nitrate nitrogen. To manage the water quality of the river basin two strategies are considered which are expressed by different goal functions:

(i) Ecological strategy according to the limiting nutrient concept (LNC);
(ii) Impact strategy according to the LAWA concept.

On the base of the results of optimal simulation runs proposals of decision for water quality management will be derived.

2. EUTROPHICATION PROCESS IDENTIFICATION

Within freshwater ecosystems the eutrophication processes are influenced by internal and external factors. The internal utrient remobilisation from sediments stimulates an increase of algal biomass. The external meteorological and hydrochemical conditions support the ecological conditions within the water body in different ways.

Dead organic matter as algal biomass is mineralised by micro-organisms. This process needs electron acceptors which are supplied from the water column where nitrate and dissolved oxygen are the major electron acceptors before iron is consumed. The order of consumption is determined by the Gibbs free energy gained in the reaction. Methane formation due to decay of organic material in sediments leads to an increase of nitrogen and phosphorus within the pore water of sediments.

Nutrients enter the sediment by molecular diffusion, convection, or bioturbation. In the case of aerobic conditions phosphate will be fixed in the sediment. Anaerobic conditions and formation of hydrogen sulphide cause a destruction of the iron(III)phosphate and iron(III)hydroxide layer of the mud-water interface which prevents phosphorus remobilisation under aerobic conditions. This process leads to a diffusion of phosphorus from pore water to the water column. The process model concept is shown in fig. 1.

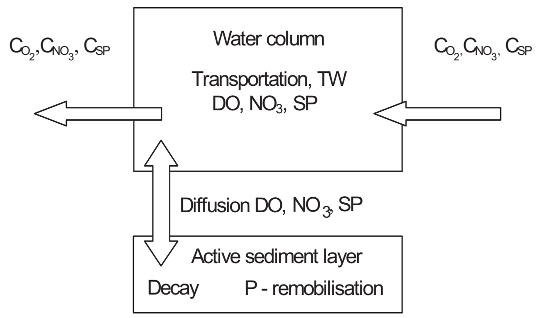

Figure 1 Process model concept of P-remobilisation (SP–soluble phosphorus, DO–dissolved oxygen, NO3–nitrate nitrogen)

The respective sub-model equation is given by

dPSED/dt = (-1)Θ·phi·hs(-Dsp/(1-ln(phi2))(P-(PSED/(hs·phi)))/hs/2 + Θ (cpcrit-cpEA/cpcrit)·(KFe CpFe+qp))

where Θ =1, if CpEA ≤ cpcrit, and Θ = 0, if CpEA > cpcrit.

The parameters are phi – sediment porosity, hs - thickness of active sediment layer (m), Dsp – diffusion coefficient of dissolved phosphorus, P – dissolved phosphorus, CpFe – iron concentration in pore water, qp - ratio P/Fe of reducible iron, KFe – iron concentration in pore water with KFe = K_1(TW)/36, cpcrit – critical value of CpEA, K_1(TW) = K_1(20) $(0.1)^{(TEMP - 20)}$ – temperature dependent decay rate of organic material in pore water, K_1(20) – standardised decay rate organic material in pore water at 20°C, cpO_2 – dissolved oxygen concentration in pore water with cpO_2 = O_2/31,998, $cpNO_3$ – nitrate concentration in pore water with $cpNO_3$ = NO_3/14.007, cpEA – electron acceptor concentration in pore water with cpEA = $2cpO_2$+$5cpNO_3$. A more detailed description of parameters is given by [3].

3. THE COTTBUS EUTROPHICATION SIMULATOR CEUS

To simulate the eutrophication process in freshwater bodies a stationary 1D-simulator was developed. The model concept is presented in fig. 2.

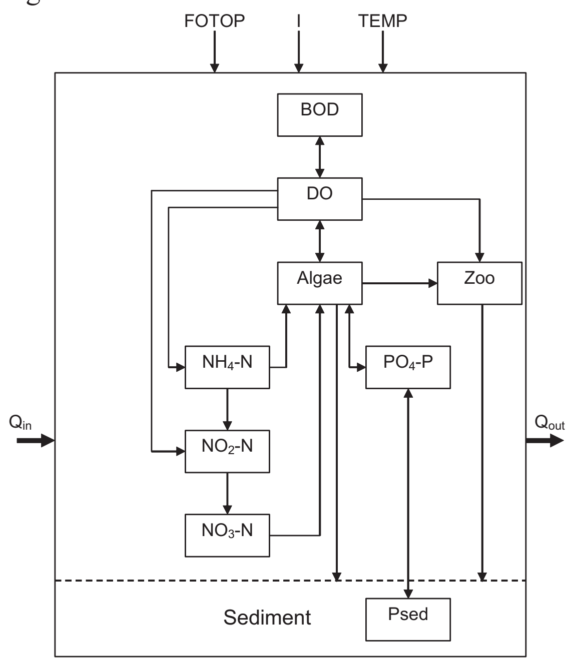

Figure 2 Conceptual model of the eutrophication simulator

Model state variables are given by the water quality indicators phytoplankton (algae), zooplankton (Zoo), orthophosphate phosphorus (PO_4-P), ammonia nitrogen (NH_4-N), nitrite nitrogen (NO_2-N), nitrate nitrogen (NO_3-N) as well as by dissolved oxygen (DO) and biochemical oxygen demand (BOD).

To cover the phosphorus remobilization process from sediment the submodel (PSED) given above was included in the phosphorus balance equation assuming that a quarter of soluble phosphorus is originated by P-remobilisation from sediment. Detailed descriptions of model equations, parameters, site constants and system specific parameters are described by [3]. Q_{in} and Q_{out} describe the discharges into and out of the river segment or lake under consideration. External driving forces are photoperiod (FOTOP), solar radiation (I) and water temperature (TEMP) [6]. The input to each river-lake segment is given by three input boundary conditions for dissolved oxygen, nitrate and soluble phosphorus.

4. PARAMETER OPTIMISATION

To support manufacturing, organisational and logistic processes the software tool for modelling and optimisation ISSOP (integrated system for simulation and optimisation) was developed by [5]. Figure 3 shows the ISSOP architecture.

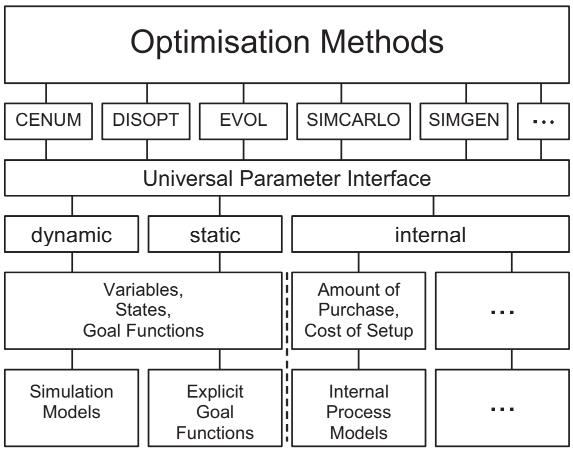

Figure 3 The ISSOP architecture

The following optimisation procedures are included: component wise enumeration, a quasi-gradient method, an evolutionary optimisation strategy, optimisation by MCM, optimisation by a genetic algorithm. Other optimisation procedures can be added.

This tool was combined with CEUS by using the implemented universal open MATLAB interface [4]. Input variables of the simulation system are denoted by $\alpha_1 x_1,...,\alpha_k x_k$, outputs are symbolised by $y_1,...,y_m$ respectively (fig. 4).

Goal functions are denoted by $f_1,...,f_n$ with $fi(M(\alpha_1 x_1,...,\alpha_k x_k)) = f_i(y_1,...,y_m)$ where $i = 1,..., n$, and arbitrary continuous functions can be used. They will be optimised simultaneously. If $n > 1$, the goal functions $f_1,...,f_n$ are aggregated to a (weighted) sum $S = \Sigma w_i\ f_i$ with $\Sigma|w_i| = 1$. w_i are weighting factors. ISSOP uses the model variables and target values as input data and gives optimized state variables back to the simulation system.

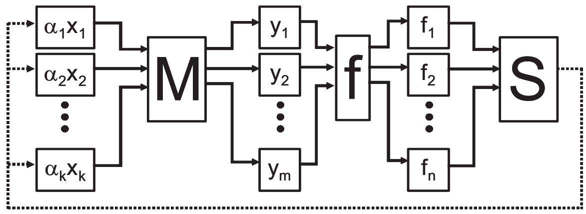

Figure 4 Coupling of ISSOP with CEUS

5. EXPERIMENTAL AREA

The River Havel belongs to the greatest tributaries on the right hand site of the River Elbe. It is strongly influenced by the River Spree. Both the Rivers Spree and Havel are lowland rivers with small elevation differences.

The watershed is characterized by shallow lakes, wetlands and marshy country, as well as by high evaporation rates. Hydraulic works and banked-up water levels influence the water flow and the intensity and kinetics of nutrient dynamics along the courses of the rivers. Only 25% of precipitation contributes to flow. For the water quality simulation framework the river stretches of interest were divided into 19 segments of different length (fig. 5). But the number of segments is not restricted.

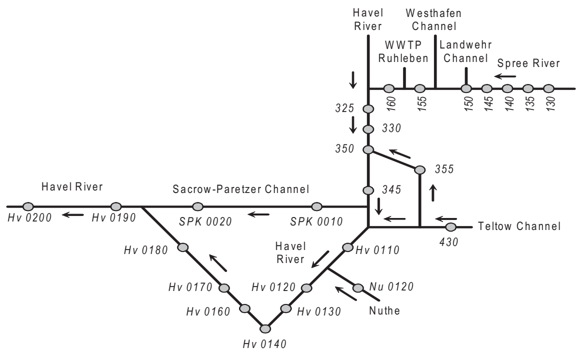

Figure 5 Segmentation of rivers Spree and Havel

The model concept given above is valid for each river segment. Long-term administrative data sets from water authorities of the State of Berlin and the State of Brandenburg are used as input information. After validation procedures the eutrophication simulator was used to carry out basic simulations for the rivers Spree and Havel.

6. SIMULATION RESULTS

Simulation results obtained show changes in biomass and nutrient contents along the course of rivers Spree and Havel. As can be seen from fig. 6 two algal blooms take place during a year.

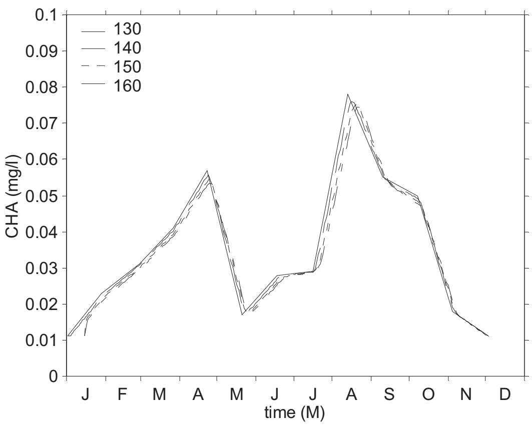

Figure 6 Biomass production along the course of the river Spree at Berlin

A slight shift of maximal biomass concentration from starting point of simulation to the mouth of river Spree is observed. This result is in accordance with increasing water quantity due to waste water input. Continued simulation runs up to the City of Brandenburg lay out that biomass increase is caused by nitrogen uptake of cyanobycteria while increase of dissolved phosphorus is caused by remobilized P from sediment.

In fig. 7 selected results of basic simulation runs are demonstrated. In accordance with natural observations phosphate phosphorus (grey lines) is decreased in spring due to consumption by diatoms. The increase in late summer is caused by phosphorus remobilization from sediment. On the other hand, phytoplankton maxima in late summer/early fall are caused by cyanobacteria which utilize nitrogen as nutrient. These conditions lead to high growth rates of phytoplankton but also to high decay rates of dead organic material. Especially in late summer and fall anoxic conditions on sediment surface hold. From fig. 7 can be seen the same amount of soluble phosphorus as at the beginning of the year.

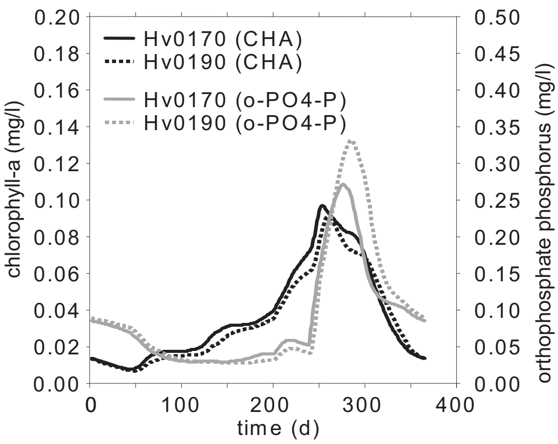

Figure 7 Basic simulation runs for phytoplankton and orthophosphate phosphorus

The yearly phosphorus dynamics is determined by two different processes: A decrease of phosphate phosphorus due to phytoplankton uptake by diatoms in spring, and an extremely increase due to phosphorus remobilization from sediment in fall. Because of nutrient rich water body the bioproduction in spring and late summer is high. During the first months of a year the growth of diatoms can be seen while in late summer green algae and cyanobacteria dominate.

In late summer and fall algal blooms collapse and lead to anoxic conditions at the sediment-water interface due to high decay rates of dead organic matter accompanied by high rates of oxygen consumption.

Management options will then be obtained by scenario analyses with changing parameter values. Two control strategies are taken into consideration. The first one is based on the limiting nutrient concept of algal biomass (LNC). The second one refers to target values of German Working Group LAWA for water quality management. Input variables of the simulator are denoted by x_1 (phytoplankton biomass), x_2 (orthophosphate phosphorus) and x_3 (nitrate nitrogen), output variables y_1, y_2, and y_3 respectively.

To get optimized results for the model transfer function $M(\alpha_1 x_1, \alpha_2 x_2, \alpha_3 x_3) = (y_1, y_2, y_3)$ the following goal functions are considered:

1. Phytoplankton biomass $f_1(t) = \Sigma_x \Sigma_t\, y_1(x, t) \rightarrow \min$.
2. Orthophosphate phosphorus $f_2(t) = \Sigma_x \Sigma_t\, y_2(x, t) \rightarrow \max$.
3. Nitrate nitrogen $f_3(t) = \Sigma_x \Sigma_t\, y_3(x, t) \rightarrow \max$.

Corresponding to the input variables following restrictions are valid for the parameters α_i (i

$= 1,..,3)$: $\alpha_1 = 1$, α_2 and α_3 vary in the interval [0,1].

Weights according to the limiting nutrient concept: $w_1 = 90.5$, $w_2 = -1.1$ and $w_3 = -8.4$: An eutrophication control according to the limiting nutrient concept leads to a diminished phytoplankton maximum in late summer due to optimised nitrate concentrations (fig. 8). No effect of optimised orthophosphate phosphorus concentration can be stated.

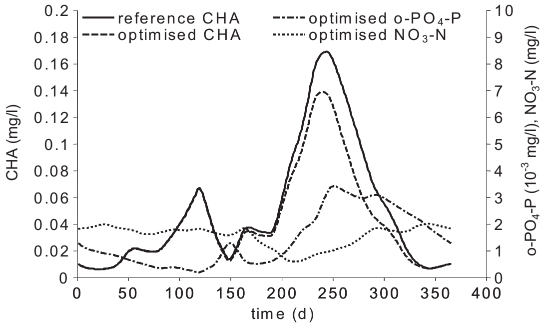

Figure 8 Water quality management according to LNC

Weights according to LAWA: $w_1 = 42\%$, $w_2 = -57\%$ and $w_3 = -1\%$ where $\alpha_2 = 0.03$ and $\alpha_3 = 0.91$. Optimized simulation results are presented in fig. 9. Eutrophication control according to LAWA target values leads to nearly the same behaviour of phytoplankton biomass in spring but to smaller differences of phytoplankton maxima and to low nutrient concentrations in late summer.

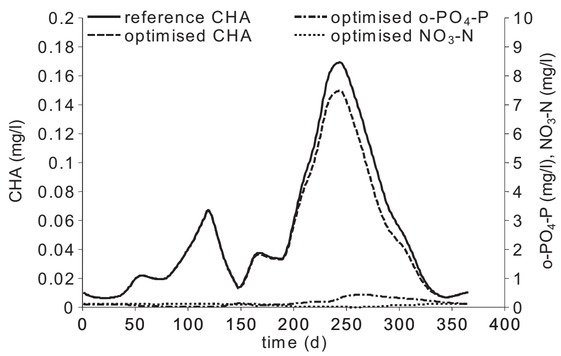

Figure 9 Water quality management according to LAWA regulations

In consequence, the LAWA strategy leads to significant lower nutrient concentrations but to a slight increase of phytoplankton biomass. In opposite of that eutrophication control by means of limiting nutrient concept results in lower phytoplankton concentrations but higher admissible nutrient inputs.

7. CONCLUSIONS

The use of combined simulation-optimisation procedures to manage the water quality of freshwater ecosystems is an approach promising more theoretical understanding of complicated natural processes and software engineering methods. Direct interrelations exist not only between trophic layers, but also between different ecosystem components. The different model approaches are constrained by the amount and the type of available data. Perspectives of developments of simulation frameworks for water quality management on a river basin scale may be seen in combinations of water quality simulation models, multi-objective optimisation procedures and visualisation tools.

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